Quantification of Surface Water and Groundwater Interactions by Coupling MODFLOW with MIKE 11: a Case Study in Hanoi, Vietnam

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1 INTRODUCTION

Interaction between surface water and groundwater is an integral process in watershed, governed by climate, geology, surface topology and ecological factors. A watershed should be envisaged as a combination of both the surface drainage area and the parcel of subsurface solid and geologic formations that underlie it (Freeze and Cherry, 1979). However, hydrologic components, such as surface water and groundwater, have historically been treated as separate units and modeled accordingly (Allison, 2008). This has made inadequate estimates of the interaction between surface and groundwater, leading to unreasonable use of water resources. As such, water managers need a tool that is able to simulate both the physical processes of flow and management objectives in order to meet demands. To fulfill this need, a linkage between two modeling tools, a surface water model and a groundwater model has been proven as a promising approach. Many authors, for example, have studied the coupling between a surface water model and a groundwater model. DAFLOW- MODFLOW was created to simulate flow in upland streams (Jobson and Harbaugh, 1999) and in their paper Jobson and Harbaugh stated that modeling results by the coupled model has higher accuracy than those by separate models. BRANCH-MODFLOW has been used in several applications, most notably to examine the effects of raising groundwater levels in the Florida Everglade on a neighboring residential community in Dade County (Swain and Wexler, 1996). FHM-MODFLOW was developed to evaluate the water budget in the Big Lost River Basin in Idaho (Said *et al.*, 2005). SWAT- MODFLOW (Jinggang, *et. al.*, 2010) has been applied to several sited in Kansas including Rattle Snake Creek and the Lower Republican River Basin (Kim, 2008). SWMM was linked to MODFLOW to characterize existing hydrology of Kearny Marsh, New Jersey Turnpike (Steven, 2010). While the coupled models above are successful for modeling the interactions of surface water in watershed, urban drainage and pipe system with groundwater, they are limited to quantify localized groundwater/surface water interaction between rivers and aquifers. Thus there is a need to develop an integrated surface-groundwater modeling tool by coupling the river flow routing model (MIKE 11) with the ground flow model (MODFLOW).

Domestic and industrial water supply in Hanoi is mainly from groundwater. Groundwater has been pumped in Hanoi since 1909 with an initial pumping rate of some 20,000 m³/day. The groundwater abstraction has rapidly increased to over 500,000m3/day at present. It is estimated up to 1,000,000m3/day in 2010 (Nguyen, 2010). Rapid growth of population and urbanization in Hanoi has put more pressures on water supply. Due to insufficiency of infrastructure, surface water, especially river and lake water has been seriously polluted. As groundwater is the most important sources of water supply in Hanoi, a great deal of groundwater related studies has been carried out. Most of these studies focused on the identification of aquifer system, land subsidence due to over withdrawal, and groundwater pollution. For example, Bui *et al*, (2010, 2011) identified aquifer system not only for Hanoi bat also for the entire Red River Delta. Modelling subsidence in the Hanoi City area, Vietnam was also conducted (Trinh and Delwyn, 2000). Arsenic pollution of groundwater in Vietnam has exacerbated for more than a century (Lenny *et.al*., 2001); groundwater pollution in the Hanoi area, Vietnam (Nguyen, 2011); research on the groundwater pollution and its effect on the community health in Hanoi, Vietnam (Bui *et.al*., 2007); hydrological and sedimentary controls leading to arsenic contamination of groundwater in the Hanoi area, Vietnam: impact of iron-arsenic ratios, peat, river bank deposits and excessive groundwater abstraction (Berg *et.al*, 2008) and so on. However, there are limited understandings on groundwater and surface water interactions in Hanoi, which is critical for effective water management and conjunctive water use planning.

This paper presents the development of a coupled MIKE 11-MODFLOW, as well as a description of its application to Hanoi, Vietnam. The emphasis in this research is on the quantification of surface water and groundwater interactions by coupling MODFLOW with MIKE 11 in order to take full advantages of each model. MIKE 11 was linked to MODFLOW through exchange of river level and groundwater level data between the models. The findings from this study provide a modeling tool with significant potential for improved operational decision-making in river reaches influenced by surface-groundwater interactions.

2 MATERIALS AND METHODS

2.1 Study area

Hanoi has a surface area of about 3,344 km^2 in the northern part of Vietnam. The population was about 6.5 million in 2009, occupying 7.5% of the Vietnam's population. The Hanoi belongs to the tropical monsoonal area with two distinctive seasons. The rainy season is from May to October and the dry season lasts from November till April. The annual rainfall is about 1,600 mm of which rainfall in the rainy season occupies about 75%. The annual average humidity is about 90% and the average temperature is around 24^{o}C. Evaporation is quite high with an annual average of 900 mm . The river network is quite dense with the density of about 0.7km/km^2. There are also more than 100 lakes with a total surface area of more than 2,180 hectares. However, the water of the Red River has a high level of suspended deposts at any one time. Due to poor infrustrure and management of dumping waste, surface water in Hanoi has been seriously polluted. Therefore, groundwater is a main source of water supply. (Bui *et. al.*,2010)

Our previous studies show that Hanoi has two main aquifers: Holocene unconfined aquifer (HUA) and Pleistocene confined aquifer (PCA) (Bui *et. al.*, 2010, 2011). HUA and PCA have highest potentials of groundwater resources for water supply in Hanoi. An impermeable layer between the two aquifers is an aquitard preventing vertical flow from the two aquifers. In some places, along the Red River, the impermeable layer is eroded completely by the river. In these places, aquifer and riverbed are interconnected and thus the interactions between groundwater and river water could be much closer than other areas.

According to hydro-geological conditions in Hanoi (Bui *et.al*, 2010), there are three main types of interconnections between aquifers and the Red riverbed: (1) the Red River contacts to the aquifer directly; (2) the Red River connects to the aquifer through hydro-geological windows; and (3) the Red river connects to the aquifer through an impermeable layer. The study area of 844 km^2 encompassing districts of Dan Phuong, Phuc Tho, Thach That, Quoc Oai, Tu Liem, Hoai Duc, Tay Ho, Ba Dinh, Cau Giay, Dong Da, Hai Ba Trung, Thanh Xuan as shown in Fig.1. The study area selected is a typical area for hydro-geological condition in Hanoi which covers three types of interactions between aquifers and the Red River mentioned previously.

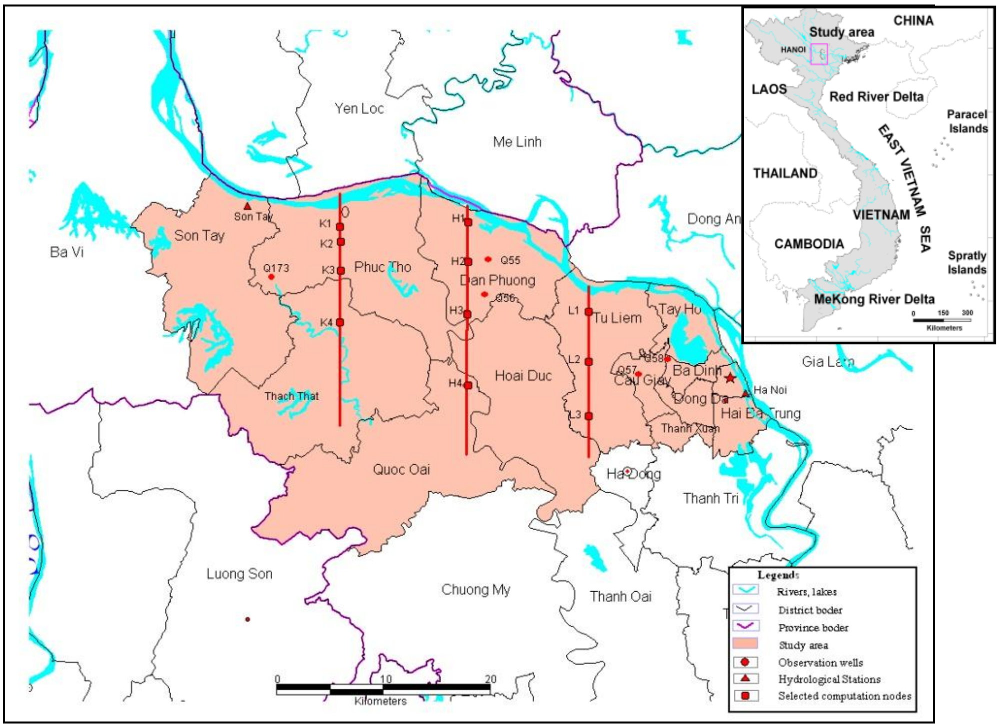

Figure 1. Study area and locations of hydrological stations, observation wells and three selected cross sections for presentation of surface-groundwater interactions.

2.2 Data used

Data used in MIKE 11 consist of: river network, cross section data from a field survey of the river in 2000 (including 119 cross sections), river water levels in Hanoi, Thuong Cat, and Hung Yen stations, inflow hydrographs (Son Tay station) in 1996, 2003 for model calibration and validation and 2006 for determining the interactions, lateral flows along river reaches, hydrodynamic parameters. The hydrodynamic parameters editor is used for setting supplementary data used for the simulation.

Data used in MODFLOW consist of: recharge and discharge data, the aquifer-system and strata geometry, the hydro-geological parameters of the simulated process and observed groundwater levels. Recharge and discharge data include the pumping volume, effective recharge (10-15% precipitation in Son Tay station) and groundwater evaporation (Son Tay station) in 1996, 2003 for model calibration and validation and 2006 for determining the interactions. They were imposed to the model through the boundary conditions or sink/source terms using the boundary packages of MODFLOW. The aquifer-system geometry was determined using the available geological information (e.g 300 well log data) and topographic maps. The hydrological parameters, including hydraulic conductivity, specific storage and specific yield, were obtained from pumping test data. The observed groundwater levels at 5 observation wells and time periods (1996, 2003) were used for model calibration and validation.

2.3 Methods

As mentioned above, the method used in this study is coupling MIKE 11 with MODFLOW. MIKE 11, developed by DHI, is a world-recognized surface water modeling package designed for simulating the hydrodynamic conditions found in rivers, lakes, reservoirs, and irrigation canals. Flexibility and speed ensure efficient modeling applications for all aspects of river engineering. MIKE 11 can be applied on applications ranging from simple design investigations to large forecasting projects including complex hydraulic structure operation policies. Through dynamic couplings to other DHI software products MIKE 11 allows to integrate rivers and floodplain modeling with models for watershed processes, detailed floodplain representation, sewer systems and coastal processes. MIKE 11 offers also links to external groundwater (DHI, 2004).

The modular finite-difference groundwater flow model MODFLOW (Waterloo Hydrogeologic Inc.) was selected to simulate the behavior of groundwater flow in the study area because it is a well-documented and extensively tested model. MODFLOW is a three-dimensional, numeric, finite difference, porous medium flow model. It contains a porous medium flow solver with several finite- difference solution methods for the groundwater equations, into which multiple hydrologic processes may be incorporated MODFLOW's formulation allows these hydrologic processes to solve independently but simultaneously, thus the model is able to represent various combination of hydrologic processes at one time. The MODFLOW software was developed to be adaptable, so users with specific needs would be able to incorporate new capabilities into its framework without requiring significant changes to the existing core code. (Harbaugh *et al*., 2000).

Visual MODFLOW and MIKE 11 have been recently developed as a fully coupled, groundwater and surface water simulation environment. This impressive combination represents the only truly conjunctive groundwater/surface water model combining USGS MODFLOW 2000and DHI's MIKE 11. Specifically, data from Mike 11 that is shared with MODFLOW replaces data that is input by the user in the River (RIV) package of MODFLOW. According to the technical description of this commercial modeling package, the coupled model could be ideally suited for a number of studies such as: analyzing the hydraulic connection between rivers, streams, and aquifer systems, determining groundwater base-flow and potential impacts to ecologically sensitive areas, calculating infiltration rates from surface water to groundwater during rainfall events, developing comprehensive watershed management plans and many others. However there has been no researches aim at testing its application capacity for actual sites so far.

3 RESULTS AND DISCUSSION

3.1 Model Calibration and Validation

The parameters referring to the hydrodynamic parameters (MIKE 11), the hydraulic conductivity, specific yield, and recharge coefficient (MODFLOW) were calibrated through an iterative process. River level from three stations i.e Son Tay, Hanoi, Thuong Cat) were used for MIKE model calibration and ground water levels from five observation wells (i.e. Q55, Q173, Q56, Q57, Q58) as shown in Fig 1 were used for MODFLOW model calibration. The calibration was performed for the period from January 1st 1996 to December 31st 1996. A trial and error method was used in the calibration process. The root mean square error (RMSE), the standard error of the estimate (SEE), the NASH and Sutcliffe model efficiency (EF) was used as indicators of goodness of fit (Moriasi *et.al.*, 2007). Both regressions show good agreements between measured and simulated river water level (Fig.2a) and ground water level (Fig. 3a), with the Nash coefficients shown as Table 1. The authors obtained RMSE = 0.47 m, SEE = 0.031 m and EF = 0.88 from five observation wells when calibrating the MODFLOW model, which are inferior to those referred above.

The models were validated for the period from January 1st 2003 to December 31st 2003. The same stations and observation wells used for calibration were used for validation. All hydraulic parameters and empirical coefficients were the same as used for calibration. Comparision of observed and simulated data showed small errors of the estimate (RMSE = 0.41 m, SEE = 0.028), high modelling efficiency (EF = 0.91) and the high Nash shown as Table 1, hence indicating that parameters were properly calibrated.

From the results of the calibration and validation, the parmeters of the models were estimated as following: bed resistance coefficient (n) : 0.02-0.55; hydraulic conductivity coefficient (K): 10-25 metter per day in the HUA and 25-60 m/d in the PCA; specific storage coefficient (Ss): 0.0001-0.003, specific yield coefficient (S_y): 0.0005-0.0125.

Table 1. The results of calibration and validation.

No	Station/Well	Model	NASH	
			Calibration	Validation
1	Hanoi	MIKE	0.87	0.86
2	Hung Yen		0.82	0.81
3	Thuong Cat		0.85	0.83
4	Q55	MODFLOW	0.83	0.81
5	Q173		0.76	0.78
6	Q56		0.88	0.85
7	Q57		0.78	0.81
8	Q58		0.84	0.83

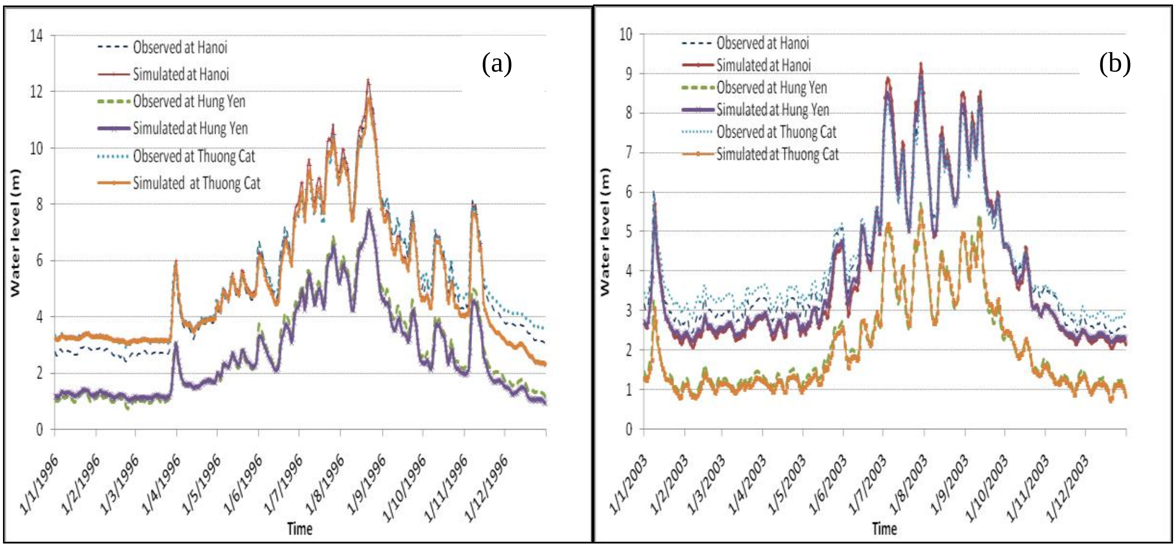

Figure 2. Comparision of observed and simulated water levels at observed stations used for (a) calibration in 1996 and (b) valibration in 2003 of MIKE 11 model.

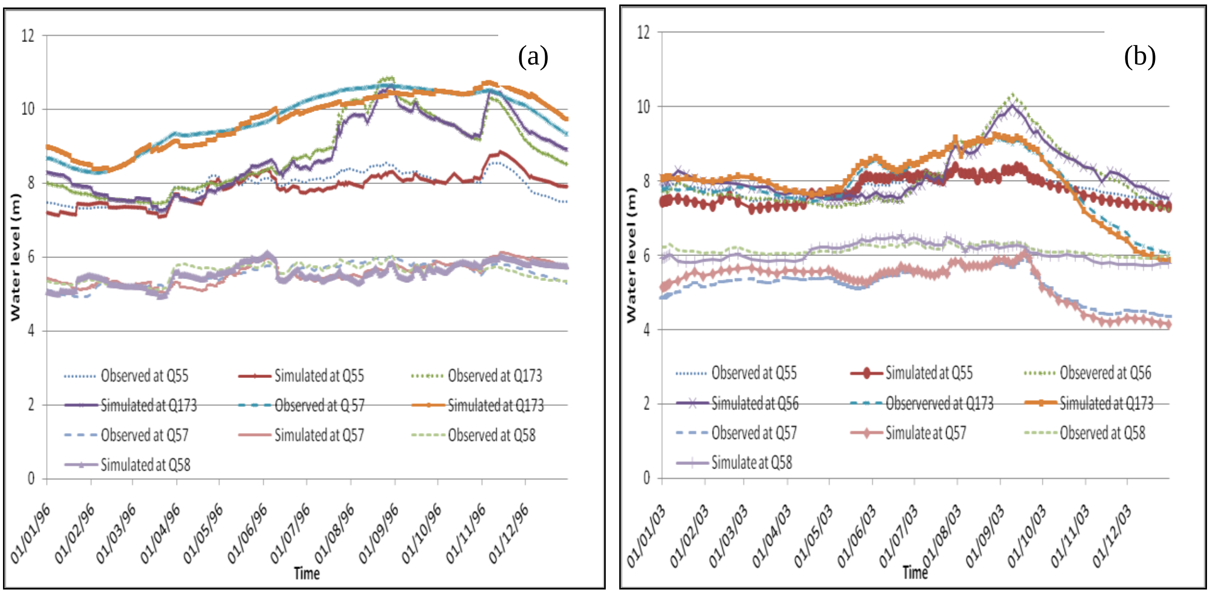

Figure 3. Comparision of observed and simulated water levels at observed wells used for (a) calibration in 1996 and (b) valibration in 2003 of MODFLOW model.

3.2 Interactions between the Red river and groundwater

3.2.1 Interactions between the Red river stages and groundwater levels in the Holocene unconfined aquifer

Table 2 shows distance to the riverside, average amplitude of the annual cycle of fluctuation, correlation coefficient between groundwater level in the HUA and the river level in nodes K1, K2, K3, K4, H1, H2, H3, H4, L1, L2, L3, L4 (Fig.1). It is noted that in node H4, L3, L4, the HUA does not exist. As shown from Table 1, the correlation coefficients vary in a wide range, from 0.74 to 0.95 with a decreasing tendency with distance from the river.

Table 2. Characteristics of water level fluctuation and the hydraulic interactions between groundwater in Holocene unconfined aquifer and the river.

No	Node	Distance from the riverside (m)	Amplitude of fluctuation (m)	Correlation coefficient
1	K1	100	8.43	$R^2 = 0.95$
2	K2	500	7.35	$R^2 = 0.93$
3	K3	1200	5.86	$R^2 = 0.91$
4	K4	2800	4.23	$R^2 = 0.81$
5	**H_1**	100	8.23	$R^2 = 0.89$
6	**H_2**	1400	8.42	$R^2 = 0.92$
7	**H_3**	3000	7.91	$R^2 = 0.9$
8	**H4**	4800	NA	NA
9	**L1**	100	8.01	$R^2 = 0.85$
10	**L2**	500	3.21	$R^2 = 0.74$
11	**L3**	4800	NA	NA

Note: NA- No aquifer available

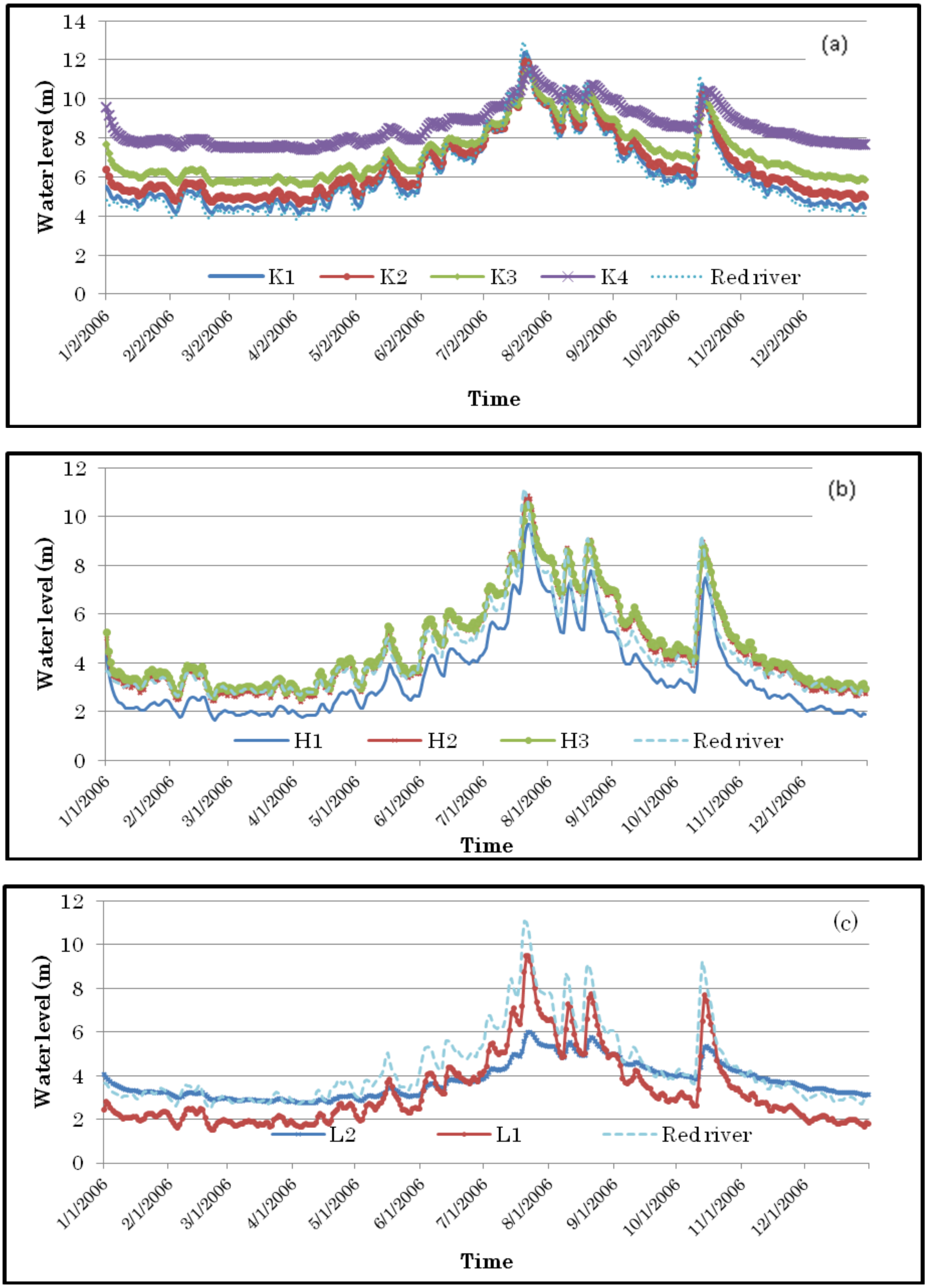

Figure 4. Fluctuation of water level in Red river and groundwater levels in the HUA at nodes: (a)K1, K2, K3, K4; (b) H1, H2, H3; (c) L1, L2.

Furthermore, we draw Fig.4 to show the visual presentation of the relationship between river water levels and groundwater levels over the time of a year. From Fig. 4, we found that fluctuation of water levels in all wells was similar to the water levels in the river. The water levels in nodes farther from the river appeared to follow the downward trend representative of the regional groundwater system. Water level in the Red river is lower than ground water levels in node K1, K2, K3, K4 almost of throughout the year (Fig. 4a). This means ground water recharged to the river during almost time of the year. In contract, water level in the river is higher than groundwater levels in node L1, L2 over almost the year (Fig. 4c) which indicates that water was flowing from the river into the aquifer. Fig. 4b shows that the ground water levels in node H3, H2 were higher than the Red river levels but ground water level in node H1 was lower. Thus, the interactions between ground water and the river were highly varied depending on the distance from the river. Water levels in all nodes increased coincident with the high stream flow events from June to August, 2006 (Fig. 4). These groundwater level rises are consistent with increased recharge to the aquifer from river leakage.

3.2.2 Interactions between the Red river and groundwater in the Pleistocene confined aquifer

Similar to Table 2, Table 3 shows distance to the riverside, amplitude of fluctuation, correlation coefficient between groundwater level in the PCA and the river level in nodes H1, H2, H3, H4, L1, L2, L3. Table 2 reveals that the correlation coefficients vary from 0.7 to 0.89, with an increasing tendency from far to near the river. Aside from this observation, Table 2 also indicates a decreasing tendency of the correlation coefficients from upstream to downstream along the river.

Like nodes in the HUA, water levels in nodes in the PCA which are near to river responded more rapidly to changes in river stage (Fig. 5). The rapid response to changes in stage in the near-river nodes is consistent with hydro-geological conditions at those locations. The difference in the magnitude of the response to river stage fluctuations among the near-river wells may result from differing hydraulic properties in the near-river aquifer and streambed material, and the resulting amount of leakage from the river. The observations of the spatio-temporal pattern of the interactions between river water levels in the Red River and groundwater levels of PCA are quite similar to those of HUA.

Table 3. Characteristics of water level fluctuation and the hydraulic interactions between groundwater in Pleistocene confined aquifer and the Red River.

No	Node	Distances from the riverside (m)	Amplitude of fluctuation (m)	Correlation coefficient
1	K1	100	NA	NA
2	K2	500	NA	NA
3	K3	1200	NA	NA
4	K4	2800	NA	NA
1	**H_1**	100	8.84	$R^2 = 0.89$
2	**H_2**	1400	7.45	$R^2 = 0.88$
3	**H_3**	3000	6.91	$R^2 = 0.85$
4	**H_4**	4800	3.59	$R^2 = 0.79$
5	**L1**	100	8.53	$R^2 = 0.88$
6	**L2**	500	6.27	$R^2 = 0.89$
7	**L3**	4800	2.32	$R^2 = 0.7$

Note: NA- No aquifer available

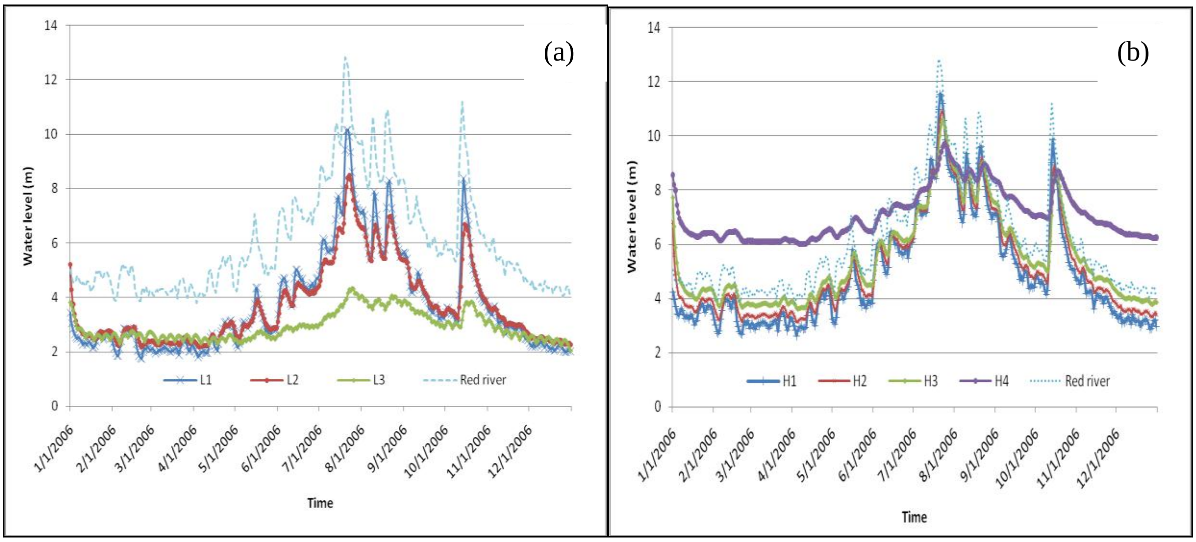

Figure 5. Fluctuation of water level in Red river and groundwater levels of the PCA at nodes: (a) L1, L2, L3; and (b) H1, H2, H3, H4.

3.2.3 Discussion

The result shows that the correlation coefficients between the river and groundwater in the HUA were higher than those in the PCA. The reason of this is that the HUA is the topmost aquifer which is affected directly by rainfall and the river water. Conceptually, groundwater in the shallow near-river aquifer has a steep gradient away from the river or is a mound of the water table underlying the river that exists only because of recharge from the river (Rodney, *et al.*, 2003). Therefore, water levels in the near-river aquifer are controlled by hydraulic properties of the aquifer material and the amount of local recharge from the river, in combination with water level fluctuations of the regional system.

Understanding the relationship between surface water and groundwater, we may reveal the possible causes leading to degradation of groundwater quality. That is because of decrease of the recharge sources to the aquifers. The recharge sources to the ground water for the study area are mostly from rainwater and surface water. In addition, the results of this study also help managers in the operation of reservoirs upstream.

One of the most severe consequences of excessive groundwater pumping in Hanoi is decline of groundwater level (Bui, *et al*., 2011). The close relationship between river water and groundwater found in this study area reveals a clear indication of reduction of water in river as the water flowing in rivers during low flow period mostly comes from seepage of groundwater into the streambed. Declines of groundwater level can alter intercept of groundwater flow that discharges into river. The ultimate effect is a loss of riparian vegetation and wildlife habitat.

Furthermore, it is also noted that the observation wells and hydrological stations in study area as shown in Fig. 1 are very limited. Most of analysis results and interpretations that were described previously are based on simulated data. The findings of spatio-temporal pattern of surface-groundwater interactions would provide more insights and higher accuracy if there were more observation wells and hydrological station in the site. The modeling approaches presented in this study would be an effective approach for similar study for poorly gauged or ungauged areas.

Although the annual cycle in groundwater levels and its strong linkages to rainfall and surface water have been also clarified in Bangladesh (Shamsudduha et al. 2009), Spain (Sanz et al. 2011), and Wisconsin, USA (Ghanbari and Bravo 2011), the levels of correlation and the mechanism of interaction between surface water and groundwater somehow different from those in Hanoi. More interesting, the close interactions between surface water and groundwater were found not only in unconfined aquifer (HUA) but also in confined aquifer (PCA) that were rarely exist in other deltas in the world.

4 CONCLUSION

This paper present an attempt to determine the spatio-temporal patterns of the interactions between the surface water of the Red River in Hanoi and the groundwater of two main adjacent aquifers, the Holocene unconfined aquifer (HUA) and Pleistocene confined aquifer (PCA). Coupling the river flow routing model MIKE 11with the groundwater flow model MODFLOW allowed to simulate the interactions between surface water and ground water in Hanoi, Vietnam. The calibration and validation of the models provided for an adequate parameterization relative to the processes influencing the recharge and discharge between the Red River and aquifers. The simulation results for three selected cross-sections revealed that there are very high correlation between the river water levels and HUA groundwater levels. It was also found that the correlations were highly influenced by the hydrogeological conditions of the aquifer and riverbed. The correlation was found decreasing not only with distance from the river, but also along the river from upstream to downstream. Upper parts of the river exhibited seasonal interactions of recharge and discharge between the river and the aquifers, while the lower parts of the river recharged the groundwater almost throughout the year. Although the correlation between the river water and PCA groundwater levels was also high with the similar tendency to HUA, it was rather small due to the existence of a thin aquitard between the two aquifers in a major portion of Hanoi.

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